North Pacific Acoustic Laboratory: Analysis of Shadow Zone Arrivals and Acoustic Propagation in Numerical Ocean Models

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LONG-TERM GOALS

My long-term goal is a complete and thorough understanding of the properties of acoustic pulses sent over megameter scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals.

OBJECTIVES

This work aims to determine the extent to which existing models of ocean variability can be used for the study of long-range acoustics. To accomplish this goal, new tools are to be developed to manage the often large size of the model output, to extract and construct the relevant acoustic properties (e.g., full-depth sections of sound speed) from the model output, and to make the acoustic calculations. Another objective is to examine data obtained on deep hydrophone arrays during the SPICEX experiment to establish general properties of receptions that occur in the shadow zone.

APPROACH

This project consists of two separate, but not entirely unrelated, investigations. First, long-range acoustic data obtained in the North Pacific during LOAPEX (Long-range Ocean Acoustic Propagation Experiment) and SPICEX (Figure 1) are to be analyzed to develop a quantified, phenomenological description of stable "ray like" arrivals measured by deep hydrophone arrays. These arrivals appear at travel times asociated with the lower cusps of the acoustic time front predicted by ray calculations, but the depth of the receiver lies well below the depths of the predicted cusps (Dushaw et al. 1999) (Figure 2). The phenomenological description of these "shadow-zone" arrivals will be used to test the results from theorists and numerical modelers striving to explain the origin, and calculate the properties, of these arrivals. Second, state estimates from high-resolution ocean models for the North Pacific, e.g., 3-D fields of temperature and salinity, are to be used to examine their suitability for making accurate long-range acoustic calculations. Given the difficulty and expense of accurately characterizing the ocean environment for acoustics by data, model state estimates may eventually provide a way to obtain time-dependent acoustic environments for acoustic studies, or for accurate acoustic predictions, over long ranges. Since numerical ocean models are at present mesoscale resolving at best, it is expected that the effects of internal waves will be modeled separately and combined with the ocean model state

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estimates to approximate the acoustic environment as best as possible. Whether the ocean model state estimates can be used to predict the properties of shadow-zone arrivals or not is an open question.

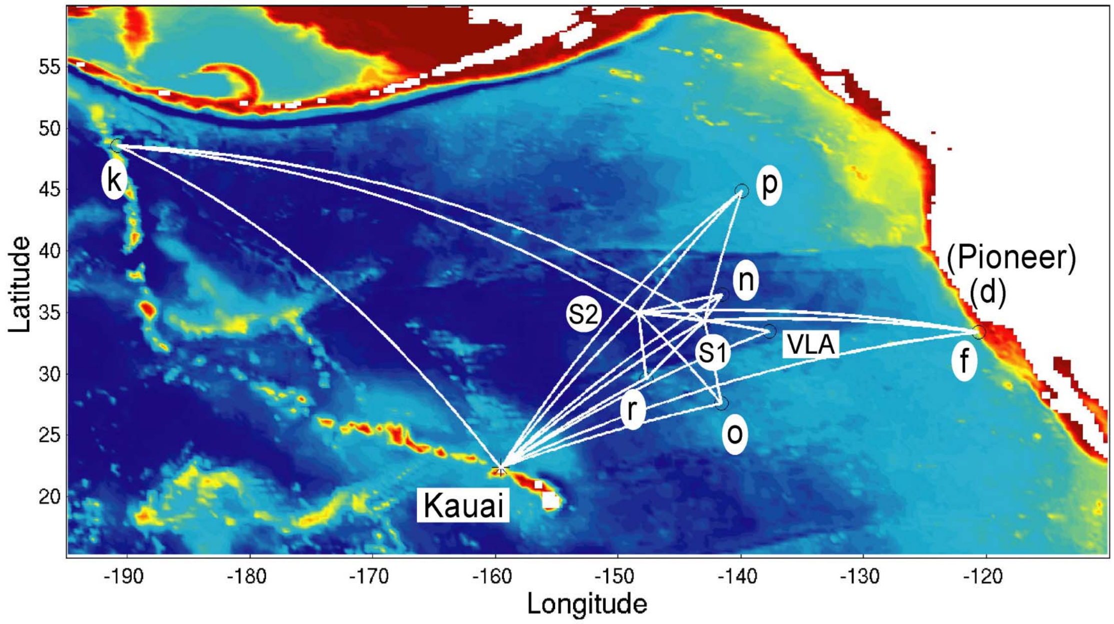

Figure 1. The 2004 NPAL Array.
[The 2004 NPAL Array consisted of three SPICEX moorings labeled S1, S2, and VLA, augmented by the 75-Hz Kauai acoustic source and SOSUS receivers denoted f, k, n, o, p, and r.]

WORK COMPLETED

Most of the effort this first year of the project has been directed toward acquiring, assembling and organizing the various components that are required to get the analysis underway.

Data recording shadow zone receptions at deep SOSUS receivers n and o from the 75-Hz Kauai source and SPICEX sources S1 and S2 were cataloged and a summary of those data shown at the NPAL workshop last spring. Moorings S1 and S2 actually hosted two sources: the 250-Hz broadband HLF-5 source and the 250-Hz Webb sweeper source. Shadow zone arrivals were recorded with these sources, showing that this phenomena occurs at the higher frequencies and at really rather short ranges as well. Figure 2 shows an example; this type of reception is ubiquitous.

Acoustic calculations using the RAM parabolic equation approach (Collins 1993a, 1993b) were developed and documented: (http://909ers.apl.washington.edu/twiki/bin/view/Main/RamMatlabCode). The RAM code was ported to MATLAB by M. Dzieciuch, and this is the code that I am employing. The aims of the web page are to make the RAM source code available for download and to document how to get the code up and running, while avoiding pitfalls. The web page is a wiki, which allows for collaborative contribution to the documentation through a browser.

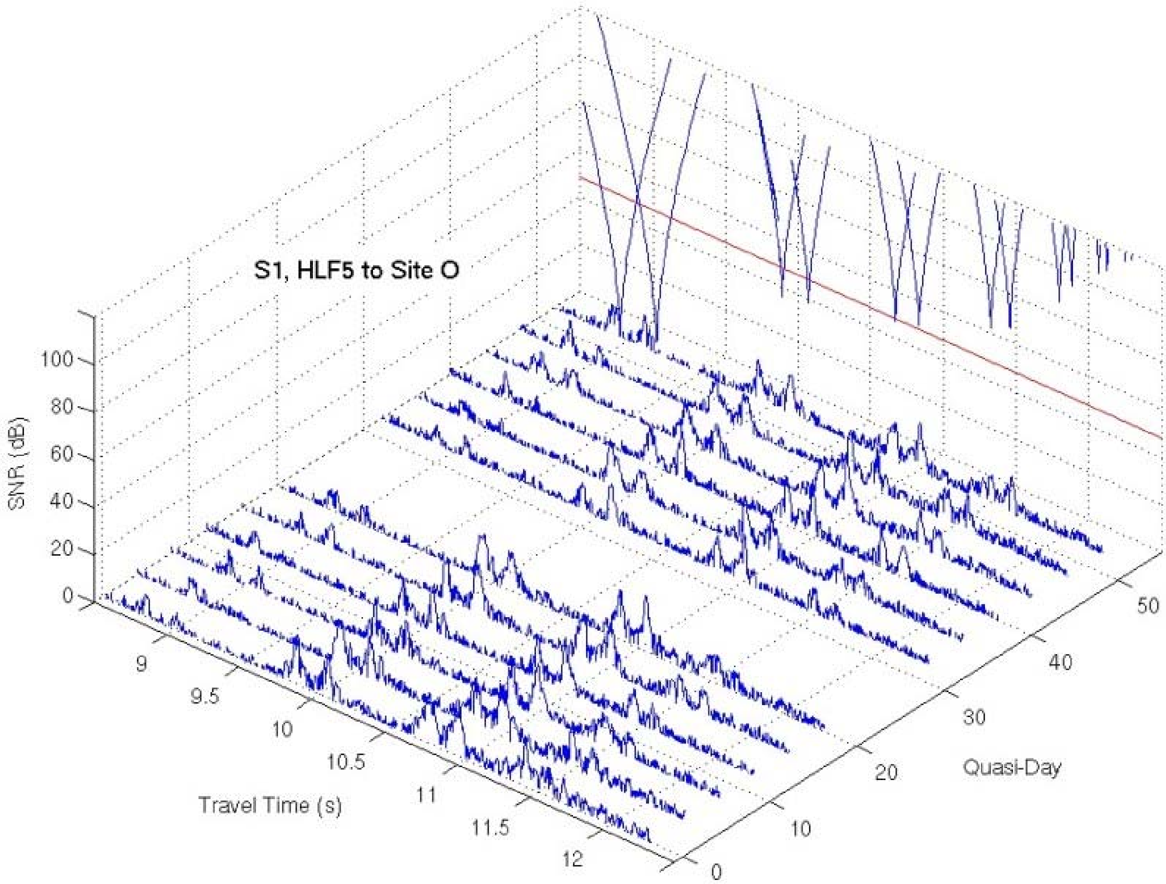

Figure 2. Shadow zone receptions from NPAL source S1 to SOSUS receiver O. [Shadow zone receptions from transmissions from NPAL HLF-5 source S1 (250 Hz), located near the sound channel axis, to SOSUS receiver O. Receptions over the course of two days are shown in the waterfall plot with 6 receptions per day. The prediction for the acoustic time front using rays is shown in the upper right, with the receiver depth denoted by the red line.]

A quad-processor computer server was acquired and configured in anticipation of the computational and storage requirements for the acoustic calculations and high-resolution model outputs. RAM calculations benchmarked on this server gave collaborators at SIO the confidence to acquire an 80 processor cluster machine, with components based on the server configuration.

Several models for the temperature and salinity in the North Pacific Ocean have been acquired. From these data sound speed can be calculated (Dushaw et al. 1993). From simple to sophisticated, these models are:

The 2005 World Ocean Atlas (Locarnini et al. 2006, Antonov et al. 2006). The world ocean atlas is an important element of this work, boring though it may be, for two reasons. First, acoustic predictions using this atlas are known to be a reasonable base state; acoustic arrival patterns calculated with this atlas are reasonably accurate in their absolute travel time and dispersal of the multipath travel times. The atlas thus provides an important test for the acoustic accuracy of more sophisticated numerical ocean models. Figure 3 shows a comparison of data obtained on the Kauai source to receiver k (see Figure 1) acoustic path with ray predictions using the monthly realizations of the atlas. For this work, the ray code employed is that of Dushaw and Colosi (1998). Second, the sound speeds derived from the atlas can be used to correct or replace missing values of sound speed in the other atlases.

Smoothed estimates of temperature derived from available hydrography and altimetry (Willis et al. 2003, Willis et al. 2004). Willis et al. have calculated smoothed estimates of upper-ocean world ocean temperatures using hydrography (e.g., Argo float data) and altimetry. These estimates are coarse resolution and smoothed temporally with a 1-year running mean. Thus, this product does not include internal wave, mesoscale, or seasonal variability. The upper-ocean temperature profiles have been extended to the deep ocean to allow acoustic calculations using cubic spline techniques and the world ocean atlas for the abyssal values. Salinity estimates were also not yet available, salinity values were assigned using T-S relations from the World Ocean Atlas; salinity values are required to calculate sound speed.

The "Estimating the Circulation and Climate of the Ocean" (ECCO) Global Ocean Model (Marshall et al. 1997a, 1997b, http://www.ecco-group.org/). The ECCO model is a data assimilating model that attempts to incorporate all available data (e.g., altimetry, Argo float data) to estimate the ocean state. There are various flavors of ECCO ocean models; I am using the 1-degree resolution, 46-layer model from JPL that uses a Kalman filter for data assimilation (Figure 4). Newer versions of this model have greater resolution, hence may provide more realistic estimates of the ocean state for acoustics. The 1-degree model suffers from a number of problems, one of which is unphysical sound speed gradients in the time-mean state. These gradients make the results of acoustic calculations rather unphysical (if not unrecognizable), so the time-mean state of the model is replaced by the World Ocean Atlas (with the model contributing estimates of the variability). I expect that any existing model will have some pathology or another in terms of its acoustic properties; working around such issues is one of the tasks of this project.

The "HYbrid Coordinate Ocean Model" (HYCOM) for the North Pacific (http://hycom.rsmas.miami.edu/). The HYCOM model is a high-resolution, non-data assimilating model. Model runs for the North Pacific are available via a Live Access Server (LAS) (Figure 5). This model has 1/12° horizontal resolution, but, alas, only 12 level/layers ("hybrid"" means the model has mixed layers and levels). With such fine horizontal resolution, the model runs show a great deal of realism, hence they highlight possibilities for using such models for acoustic studies. However, the limited number of layers make the model marginally suitable for acoustic calculations without considerable vertical interpolation.

A high Resolution "Parallel Ocean Program" (POP) model result for the North Pacific Ocean (Maltrud and McClean 2005). J. McClean has provided model output from her high-resolution POP model runs for the North Pacific. With 0.1-degree horizontal resolution and 40 levels with depth, this non-data assimilating model is mesoscale resolving, which should be ideal for acoustic purposes. I recently obtained the model data and no progress has been made with it yet. The model apparently has an awkward internal grid geometry for computational purposes, so a bit of effort was required by McClean to extract it to a user-friendly form.

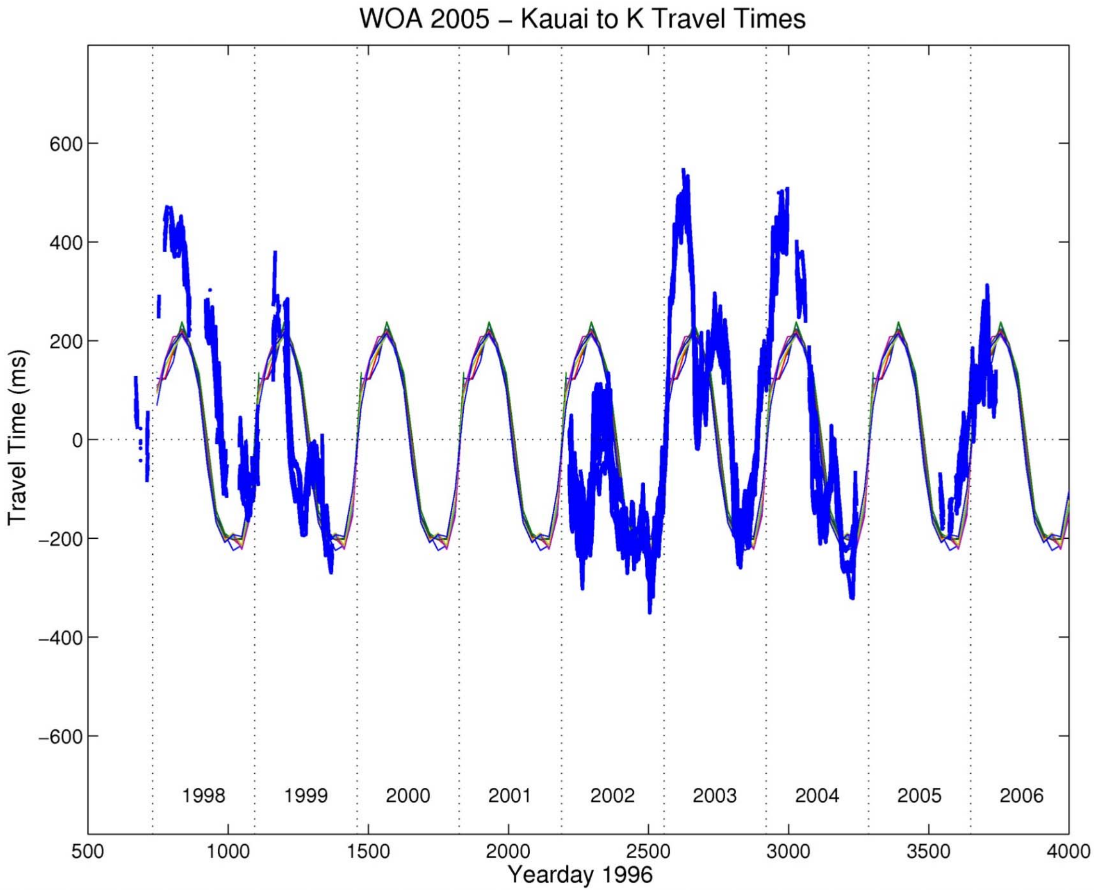

Figure 3. Measured and Calculated Travel Times for the Kauai to k Acoustic Path. [The heavy blue lines show the measured resolved-ray travel time variability on the Kauai to "k" acoustic path. The colored lines show equivalent rays calculated using the 2005 World Ocean Atlas for this acoustic path. Results from the 12 monthly realizations in the atlas are repeated over this 9 year duration. See also Dushaw et al. 1999.]

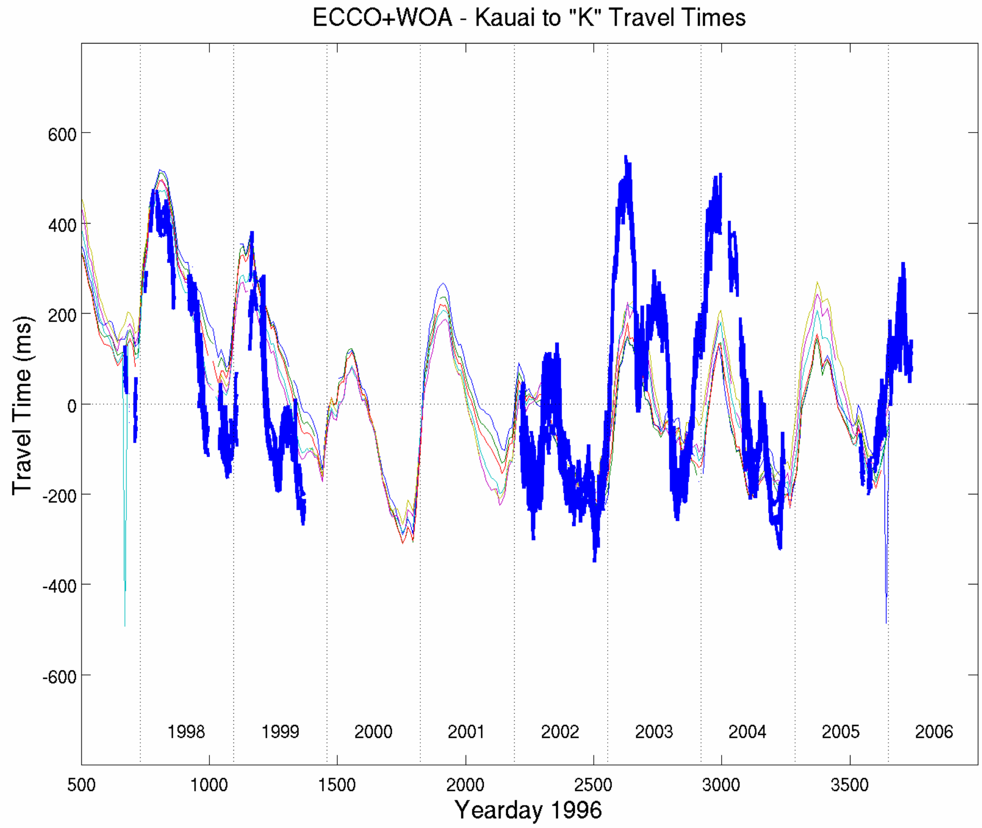

Figure 4. Measured and ECCO Model Travel Times for the Kauai to k Acoustic Path. [The heavy blue lines show the measured resolved-ray travel time variability on the Kauai to "k" acoustic path. The colored lines show equivalent rays calculated using the ECCO ocean model for this acoustic path. The ECCO model time-mean state has been replaced by the 2005 World Ocean Atlas to avoid unphysical, time-independent variations of temperature with depth in the model.]

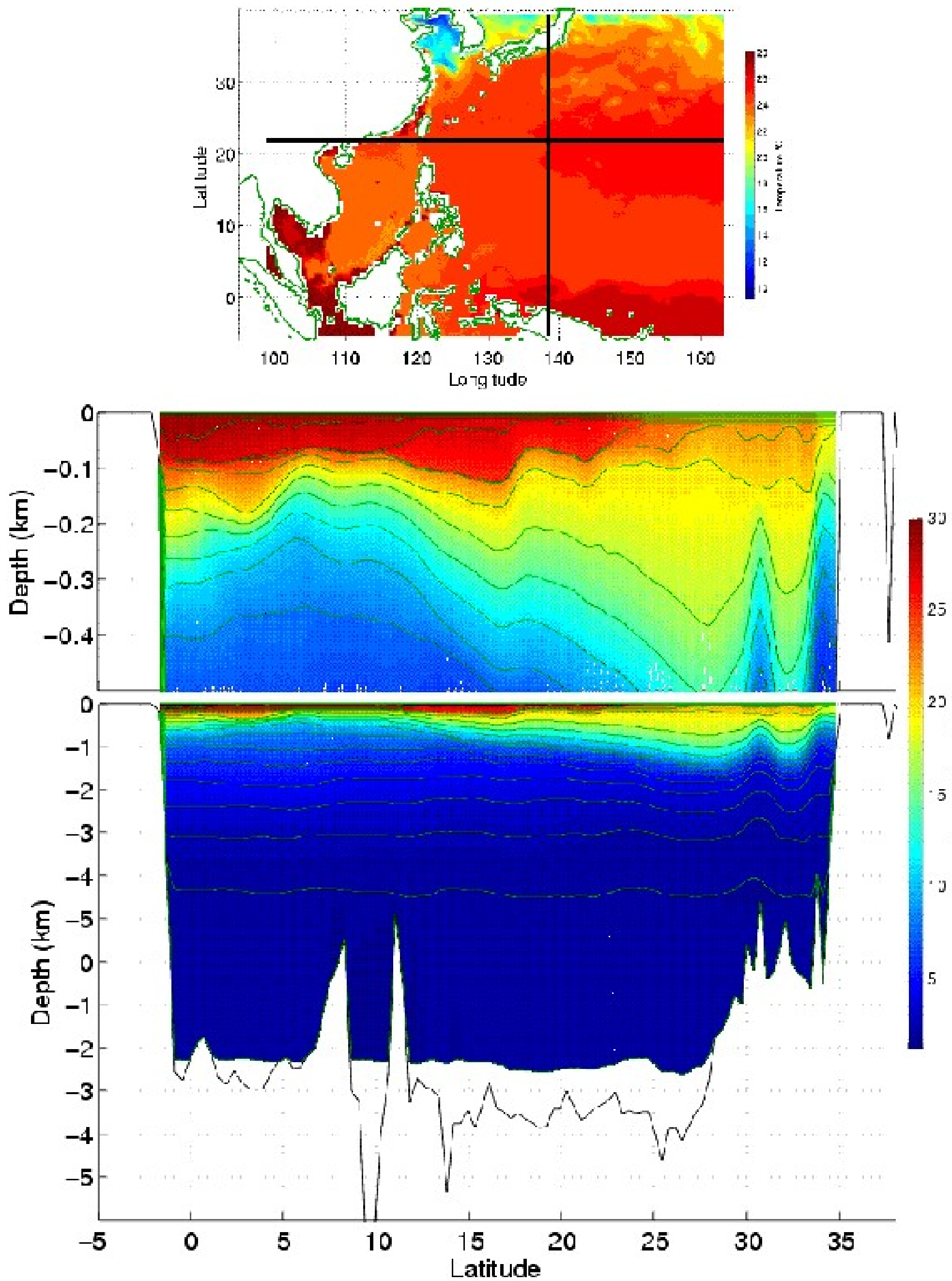

Figure 5. An Example of a High-Resolution Model: HYCOM.
[The top panel shows a snapshot of a layer of the model at about 300 m depth in the Philippine Sea. The bottom panel shows a temperature section along the meridional section shown in the top panel. This model has 1/12° horizontal resolution, but with only 12 layers in the vertical it is marginal for accurate acoustic calculations.]

RESULTS

Other than the nuances of extracting realistic sound speed sections from the ocean state estimates, there are no meaningful technical results to report yet. The main effort has been directed at manipulating the oftentimes large model data files, and merging those data with acoustic propagation capabilities. This effort is still underway. It is clear that the model results are not generally directly suitable for acoustic calculations. Constraints preserving essential acoustic properties might be a useful consideration in future model development.

Acoustic arrivals in the shadow zone were ubiquitous in the data obtained from deep receivers during the SPICEX/LOAPEX experiment. This rich data set looks as if it will be very useful for deriving general properties of this type of acoustic arrival.

IMPACT/APPLICATIONS

Ideally, at some point, data-assimilating models will have enough resolution and data constraint that they can be used for accurate, real-time predictions of acoustic properties over any ranges anywhere in the world. This work aims to assess present capabilities, and perhaps develop criteria or constraints for better behaved acoustics that modelers can begin to implement.

The acoustic properties of shadow-zone arrivals, including the basic oceanography+acoustics that gives rise to them, are fundamentally not well understood. These properties are relevent to the design of deep acoustic observing systems.

RELATED PROJECTS

This project is a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, comprised of researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (http://npal.ucsd.edu/)

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